Research on Dynamic Control of Robot Joint Based on Neural Network

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Abstract. With the rapid development of intelligent manufacturing and automation technology, the dynamic control of robot joint has become the key technology to achieve high precision and high efficiency. Traditional control methods, such as PID control, although they perform well in some applications, their performance is limited in the face of complex nonlinear systems and real-time requirements. This paper reviews the robot joint dynamic control method based on neural network, and discusses the use of deep learning technology to improve the precision and adaptability of robot control. Firstly, the basic concepts of robot joint control are introduced, including position control, speed control and force/torque control. Then, the application of neural network in robot control is analyzed, including inverse dynamics modeling, trajectory tracking control and adaptive control. The paper further discusses various neural network structures and their applications in robot control. Finally, the paper identifies key challenges and future directions for neural network-based robot joint dynamic control. These include adaptive control strategies, integration of deep learning and reinforcement learning, and model predictive control (MPC). Other aspects like multi-modal perception and fusion, hardware implementation, edge computing, human-machine collaboration, interpretability, generalization, standardization, and modularization are also discussed. The purpose of this paper is to provide a comprehensive technical reference and guidance for future research directions for researchers and engineers in the field of robot control.

Keywords: Neural network, Dynamic control, Robot joint, robot.

1. Introduction

As an important pillar in the field of modern manufacturing and automation, robot technology is directly related to the quality and efficiency of work. Joint dynamic control is one of the core problems in robot technology, which involves the precise adjustment of joint position, speed and force/torque. Although traditional control methods have been successful in some application scenarios, they gradually show their limitations in the face of increasing complexity and dynamic requirements. Especially when the system presents a high degree of nonlinearity and uncertainty, the traditional control algorithms are difficult to meet the needs of real-time, accuracy and robustness. Neural networks, particularly deep learning technologies, offer new solutions for robot joint dynamic control due to their advantages in handling complex nonlinear systems. The neural network can learn the internal laws of the system from a large amount of data, and realize the precise control of the robot joint without relying on the exact physical model. In addition, the self-learning ability of the neural network enables it to adapt to environmental changes and the drift of system parameters, thus improving the adaptability and robustness of the control strategy. This paper first introduces the basic concept of robot joint dynamic control and traditional control methods, then discusses the control strategy based on neural network in depth, and analyzes the application of different types of neural networks in robot control. Then, the steps of robot joint dynamic control based on neural network are proposed, including data collection and preprocessing, network design and training, online control and adjustment optimization. Finally, this paper discusses the main challenges and future development directions in this field, aiming to promote the progress and innovation of robot control technology.

2. Dynamic joint control of robots

2.1. Position control

Position control, as a basic method in robot dynamic joint control, plays an important role in scenarios where precise position control is required [1]. Combining with the actual requirements and working conditions, through reasonable algorithm design and parameter debugging, efficient and stable control effect can be achieved. The goal of position control is to make the joint or end effector of the robot reach and maintain a certain set target position. By adjusting the input of the joint drive (such as a motor), its output meets the required position signal. Position control usually adopts a closed-loop control system, that is, a feedback control system. The basic control loop includes five parts: reference input, sensor, controller, actuator and feedback path. The reference input is used to set the target position. Sensors are used to measure the current joint position in real time, such as encoders, optical sensors, etc.

The controller can compare the target position with the currently measured position difference (error) and calculate the drive signal based on the error. Common control algorithms include proportional integral differential (PID) control [2]. Actuator a mechanism that generates a corresponding action by receiving the drive signal output by the controller, usually a servo motor. The feedback path is to feed the current position signal back to the controller to achieve closed-loop control. Position control is widely used in various robots, the most important of which are handling and assembly robots, home robots and medical robots. Handling and assembly robots are joint robots, the precise positioning of each joint is essential to achieve complex trajectory planning and tasks, and high-precision position control is also required to ensure the correct placement and assembly of parts. Home robots and medical robots are both service robots, and home robots need precise control of their movement and obstacle avoidance, such as vacuum cleaners. Medical robots are mainly surgical robots, which require extremely high precision to perform complex surgical operations.

Position control has some advantages and disadvantages, among which advantages include high precision (can achieve very precise positioning), easy implementation (control algorithm is relatively simple, and hardware requirements are not high), and wide application (suitable for a variety of tasks requiring precise positioning).

Disadvantages of position control include sensitivity to changes in the environment (environmental interference may affect the control effect) and limited dynamic performance (may not perform as well as other control methods (such as force control) under fast motion or high load conditions).

2.2. Speed control

As a key method in robot dynamic joint control, speed control plays an important role in scenarios that require smooth and precise speed control. Through reasonable algorithm design and parameter debugging, efficient and stable control effect can be achieved to meet the needs of various applications. The main goal of speed control is to ensure that the motion speed of the robot joint is consistent with the target speed. By adjusting the input of the joint drive (such as a motor), control its output to meet the required speed signal. The typical control algorithm of speed control adopts PID control [2]. PID controller consists of three parts: proportional control (P), integral control (I) and differential control (D). Proportional control is to output the control signal proportionally according to the current speed error. Increasing the P gain can make the system more responsive, but may cause oscillations. Integral control is to integrate errors, eliminate steady-state errors, and improve the accuracy of the system. Too large a gain may cause the system to respond slowly or be unstable. Differential control is to differentiate the error, predict the error change trend, and increase the stability of the system. Too much D gain will amplify the noise.

There are many practical applications for speed control, the most common of which are welding robots, handling and assembly robots, mobile robots, and collaborative robots. Welding robots need to precisely control the speed of the joints to ensure welding quality and smoothness of the trajectory.

Handling and assembly robots require smooth speed control to avoid vibration and shock and protect parts and equipment. Mobile robots, such as automated guided vehicles (AGVs) and sweeping robots, require precise control of movement speed and steering speed for path planning and obstacle avoidance. Collaborative robots need precise speed control to ensure safety and coordination when working with humans.

Speed control has many advantages, including the ability to achieve smooth speed changes and reduce mechanical shock and vibration, suitable for scenarios requiring fast and precise speed adjustments, and suitable for a variety of tasks requiring precise speed control.

Speed control also has some disadvantages, the main ones are sensitive to environmental changes (environmental interference can affect the control effect, especially the noise impact of the speed sensor is large) and complex debugging process (the controller parameters need to be fine-tuned to obtain the best performance).

2.3. Force/torque control

Force/torque control is an important method in robot dynamic joint control, which can realize the precise control of the force or torque applied to the robot. Through reasonable sensor selection, controller design and parameter debugging, efficient and stable control effect can be achieved to meet the needs of various applications. The goal of force/torque control is to make the force or torque applied by the robot joint or end effector consistent with the set value.

By measuring the actual force or torque applied and calculating the control signal based on the error, the robot's actions are controlled to meet the requirements. It can be divided into two types: reaction control and torque control. Reaction control is a force sensor-based control method that achieves control by measuring the force applied by the end effector of the robot. The principle is that the force sensor installed on the robot end effector first measures the real-time applied force, and then transmits it to the controller, compares the difference (error) between the actual measured force and the set value, and calculates the drive signal according to the error. Finally, the actuator adjusts the action of the joint or the end effector according to the drive signal output by the controller, so that the applied force is close to the set value. Reaction control is often used in scenarios that require robots to cooperate with humans, such as collaborative robots, medical robots, etc. Through reaction control, robots can respond to forces according to human actions, achieving safe and precise cooperative operation. The second type of force/torque control is torque control. Torque control is a way to achieve control by controlling the torque of the joints. The principle is to measure the torque applied by the joint in real time through the torque sensor installed at the joint of the robot and transmits it to the controller, then compare the difference (error) between the actual measured torque and the set value, and calculate the drive signal according to the error. Finally, the actuator adjusts the action of the joint according to the drive signal output by the controller, so that the applied torque is close to the set value.

Torque control is often used in tasks that require precise torque to be applied to robot joints, such as robot assembly, force testing, etc. By torque control, the robot can achieve high-precision control of joint torque to ensure the accuracy and stability of the assembly process. Force/torque control is used in many fields, mainly in assembly tasks, grasping and handling, collaborative robots and force testing. In assembly tasks, robots need to accurately insert, connect or tighten parts. Force/torque control can ensure assembly quality. In the grasp and operation, the robot needs to adjust the force of the finger or the position of the object through the perception or torque, so as to achieve stable grasp and operation. In the process of collaborative robots, when robots and humans work together, force/torque control can realize sensitive response to human actions and collaborative operation. In terms of force testing, the robot needs to test the force characteristics of the object, and force/torque control can realize the high-precision control of torque and force testing [3].

The advantage of force/torque control is that it can realize the high-precision control of the force or torque applied by the robot, and has a strong ability to cooperate; It is suitable for tasks that require the robot to cooperate with humans or other objects; A wide range of applications, suitable for a variety of scenarios requiring precise force/torque control.

The disadvantage of force/torque control is that the sensor accuracy is high, and the precision of the force/torque sensor has a greater impact on the control effect, so it is important to choose the right sensor; Debugging control parameters are cumbersome, and the parameters of the controller need to be carefully debugged in order to obtain the best control performance. When using force/torque control to control the joint of the robot, some debugging and optimization are often carried out. The accuracy and consistency of the force/torque sensor can be ensured by calibrating the sensor, the parameters of PID controller can be adjusted by experiment or automatic tuning method (such as Ziegler-Nichols method), the filter is designed, and the filter is added in the feedback path to reduce the influence of noise on the control system, according to the actual situation, improve the mathematical model of the system, so that it can improve the control accuracy [4].

3. Robot joint dynamic control based on neural network

3.1. Background

The dynamic control of robot joints needs to deal with complex nonlinear and high-dimensional data, which makes traditional control methods (such as PID control) difficult to meet the requirements in some cases. Neural networks, especially deep learning technology, have strong nonlinear mapping capabilities and high-dimensional data processing capabilities, so they are introduced into robot control systems to improve control accuracy and adaptability [5].

3.2. The application of neural network in robot control

Neural networks have many applications in robot control, including inverse dynamics modeling [6]. Neural networks can be used to approximate the inverse dynamics model of robots, that is, to calculate the required joint torque or torque given the desired joint motion trajectory. Trajectory tracking control, through training the neural network, so that it can learn the joint motion law and control strategy, so as to realize the tracking of the expected trajectory; Adaptive control, in which the neural network can learn and adjust the control strategy in real time to adapt to changes in the environment and the robot's own parameters.

3.3. Types of neural networks

A neural network is a mathematical model inspired by the human brain and used to simulate the way the human brain processes information. Here are some common types of neural networks. Multilayer perceptrons (MLPS are the most basic feedforward neural networks, consisting of at least three layers of nodes (input, hidden, output) [7]. Radial basis function (RBF) networks use radial basis functions as activation functions and are commonly used for pattern recognition, classification, and function approximation. Convolutional neural networks (CNNS) are particularly suited for processing data with distinct grid-like topologies, such as images (2D) and video (3D). Recurrent neural networks (RNN) Networks with short-term memory capabilities are suitable for processing sequential data, such as time series analysis, speech recognition, etc. Long short-term memory networks (LSTMS) are a special type of RNNS that are capable of learning long-term dependencies and are often used in language models and machine translation. Gated loop units (GRUs) are similar to LSTMS, but have a simpler structure with fewer parameters, and can sometimes substitute for LSTMS in certain tasks. Deep belief networks (DBNS) are stacked of multiple constrained Boltzmann machines (RBMS) and are often used for feature learning and classification tasks. Generative adversarial networks (Gans) are composed of generators and discriminators that generate new, similar data through an adversarial process. Auto-encoders, which compress and decompress data by learning a representation, are often used for feature learning and dimensionality reduction. A Boltzmann machine (BM) is a type of stochastic neural network capable of learning the probability distribution of data, of which a Restricted Boltzmann machine (RBM) is a variant. Deep residual networks (ResNet) are designed to solve the problem of disappearing gradients in deep network training by introducing a residual learning framework. The Transformer network is a self-attentional mechanism-based network that is widely used in natural language processing fields such as machine translation and text summarization. CapsNet, which uses capsules to represent features at different levels, is better able to handle spatial relationships and pose changes. These neural network types have their own characteristics and applicable scenarios, and researchers can choose the appropriate network structure according to the specific problem. With the development of the research, more new neural network structures will appear (Fig. 1).

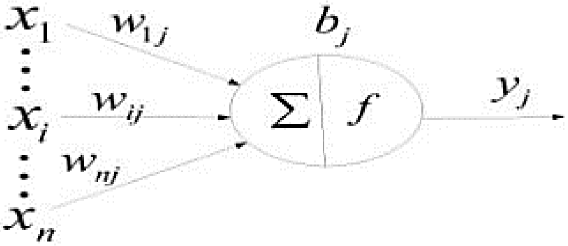

Figure 1. Convolutional network neuron model [8]

3.4. Implementation steps

The realization of robot joint dynamic control based on neural network is mainly divided into three steps. Firstly, data collection and preprocessing are carried out to collect joint motion data, including position, speed, and acceleration and corresponding control input, from physical simulation or real robot system. Then, it is necessary to carry out network design and training, design a suitable network structure according to the task requirements, and use the collected data for training. In the training process, attention should be paid to avoiding overfitting and underfitting [9]. Finally, online control and adjustment optimization are needed to integrate the trained neural network into the robot control system for real-time control. According to the actual operation effect, it may be necessary to further optimize the network parameters and training strategies.

3.5. Key challenges

The dynamic control of robot joints based on neural networks is a highly complex and active research field, which involves many challenges, the key challenges mainly include: Nonlinear and uncertain, the dynamics of robot joints are usually nonlinear and time-varying, which makes it very difficult to establish accurate mathematical models, neural networks need to be able to deal with such uncertainties and provide accurate control; Friction and vibration suppression, friction and vibration in robot joints can negatively affect control accuracy. Designing neural network controllers that can accommodate and suppress these non-ideal factors is a challenge; Real-time performance requirements, neural network controllers need to meet real-time requirements while ensuring control accuracy, especially in high-speed or high-dynamic response applications; Robustness requirements, in the face of external disturbances and model inaccuracies, the neural network controller needs to maintain stable and robust performance; Computational resource allocation capability, neural network may require a lot of computational resources, which can be a problem in resource-constrained robotic systems.

3.6. Future directions

The future development direction of robot joint dynamic control based on neural network can be discussed from multiple perspectives. The following are some possible research directions and trends: Adaptive control strategies, developing adaptive control strategies that can automatically adjust parameters to adapt to different operating conditions and task requirements [10]. This includes updating the neural network weights and structure in real time to improve control performance and adaptability; The integration of deep learning and reinforcement learning, combining the perception ability of deep learning and the decision-making ability of reinforcement learning, to design a robot control system capable of autonomous learning and decision-making in complex environments; Model predictive control (MPC), using neural network for model prediction, combined with MPC framework to achieve optimal control of robot joint dynamics, in order to improve control accuracy and response speed; Multi-modal perception and fusion, integrating multiple sensor data such as vision, touch, and force perception to improve the robot's ability to perceive the environment and control accuracy; Hardware implementation and edge computing, studying how to efficiently implement neural network control algorithm on special hardware, using edge computing technology to reduce data transmission delay and improve real-time; Man-machine collaboration, research on how to make robots better collaborate with human workers, including learning human behavior and intentions, to achieve more natural and efficient work cooperation. Explainability and transparency, improving the explainability of neural network control strategies to make their decision-making process more transparent and easy to debug and verify. Generalization ability, improving the generalization ability of neural network controllers so that they can work effectively in different types of robots and diverse operating environments; Standardization and modularization, promoting the standardization and modularization of robot control systems to facilitate the integration and interoperation of different components and systems [11].

These directions cover not only innovation at the technical level, but also consideration of the social and economic impact of robotic systems. With the continuous progress of technology, the dynamic control of robot joints in the future will be more intelligent, flexible and humane.

4. Conclusion

This paper comprehensively analyzes the robot joint dynamic control technology based on neural network, and points out its potential in improving control accuracy, adaptability and robustness. By discussing the traditional methods of position control, velocity control and force/torque control, this paper emphasizes the importance of neural network in dealing with robot joint dynamic control problems. This paper also discusses a variety of neural network structures and their applications in robot control, including multi-layer perceptron, radial basis function network, convolutional neural network, etc. It also puts forward three main steps to realize the control based on neural network. In the key challenges section, this paper discusses several important aspects: the handling of nonlinearities and uncertainties, the suppression of friction and vibration, real-time performance and robustness requirements, and the allocation of computational resources. In response to these challenges, this paper proposes a series of future directions; including the development of adaptive control strategies; the combination of deep learning and reinforcement learning; the application of model predictive control (MPC); multi-modal perception and fusion; hardware implementation and edge computing; human-machine collaboration; the enhancement of interpretability and transparency; the enhancement of generalization capabilities; and the advancement of standardization and modularization.

In general, the robot joint dynamic control technology based on neural network shows broad prospects for development. With the continuous progress and innovation of technology, the future robot control system will be more intelligent, flexible, and user-friendly, and can better adapt to the complex and changeable operating environment and meet the diversified task needs. The research results of this paper not only provide the theoretical basis and technical guidance for the researchers in the field of robot control, but also provide a new idea and direction for the further development and application of robot technology.

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